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Analysis and Estimation of Reservoir Sedimentation Using Remote Sensing and GIS

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Abstract

Periodic assessment of reservoir capacity is essential for better water resources management and planning for the future water use. Reservoirs and water storage structures raised on the rivers are subjected to sedimentation and he sedimentation is caused by deposition of eroded sediment particles carried by the streams. Knowledge of reservoir sedimentation is important to estimate avaliable storage capacity for optimum reservoir operation and scheduling water release. In recent years, remote sensing and GIS techniques have emerged as an important tool in carrying out reservoir capacity analysis and water management. The reduction in storage capacity as compared to the original capacity at the time of reservoir impounding is indicative of sediment deposition. In this study, the application of GIS and remote sensing techniques were applied to assess the sediment deposition, losses in the reservoir storage and the revised cumulative capacity. Satellite images covering Pyodongdong reservoir were analyzed using Erdas Imagine and ArcGIS softwares.Cumulative capacities at different levels were also calculated and we estimated that the revised live storage was 84.2Mft3 in 2021 and 64.3Mft3 in 2022 while the original capacity was 22.8 and 53.6Mft3 in 2021 and 2022.

Key words: *Sedimentation, Reservoir, GIS, Remote sensing, Cumulaive Capacity*

1. Introduction

A reservoir is generally located towards the end of a large watershed and receive inflows from major rivers and defined as area of land that drains water, sediment and dissolved materials to a common receiving body or outlet. It is beneficial to study hydrologic processes at reservoir scales because at such scale all inputs and outputs may be accounted for to allow us to predict the hydrologic response of reservoir[1]. For the most part, hydrologic models are based on a systems approach, and differ by how and to what extent each component of the hydrologic cycle is considered. Computer simulation models are a composite of mathematical relationships, some are empirical, and some are based on theory. As one attempts to explain or predict the impacts of reservoir management practices on increasingly complex systems, more details and complexity are needed in model formulation. This can lead to development of models that must be calibrated by fitting parameters and relationships to local reservoir conditions. Althouh reservoirs have a shorter residence time, a

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much larger watershed can be more difficult to control the water flow. Therefore, capacity surveys are important for proper allocation and management of water in a reservoir and knowledge about the quantum of sediment and its deposition pattern in various zones of a reservoir is very essential to assess the balance life of

reservoir and sedimentation. Soil is eroded due to rainfall and winds, resulting in tremendous sediment movement into watercourses by flood and storm waters. The impact of sediment erosion, transport and deposition is widespread and deposition of coarse sediments reduces the reservoir storage and channel conveyance for water supply, irrigation and causes extensive disturbance to streams.

Suspended sediments reduce the water clarity and sunlight penetration, thereby affecting the biotic life and sediments in the bottom of water bodies buries and kills the vegetation and changes the aquatic ecosystem. Therefore, efficient utilization of the water resources requires that the rivers and reservoirs must be operated in the most judicious and scientific manner. Efficient regulation of the rivers and reservoirs can lead to increased benefits from the reservoir as well as significant reduction in damage due to floods. It is therefore essential to monitor the capacities of the existing reservoirs at regular intervals and take suitable measures for controlling the sedimentation rate. To determine the useful life of a reservoir, it is necessary to periodically conduct the surveys and assess the sedimentation rate in the reservoirs. Present conventional techniques of sediment quantification in a reservoir, like the hydrographic surveys and inflow-outflow methods, are cumbersome, costly and time consuming. The inflow-outflow method involving measurement of inflows into and outflows from the reservoirs comprising discharge an sediment concentration is also being used in some cases[2]. Satellite images which have spatial, spectral and temporal attributes, can provide synoptic, repetitive and timely information about the water flow and sediment distribution in a reservoir. Using the revised surface area of the reservoir at various elevations, revised elevation-area-capacity table can be prepared and compared with the original capacity table. The reduction in the capacity can be attributed to the sediment deposition in the reservoir.

The usage of mapping and estimation of water spread from satellite image and spatial data with geographic information system GIS is well understood, and different techniques such as visual interpretation of satellite imagery, density slicing, and digital classification of water bodies have been employed for the delineation of water bodies[3]. Ashish examined a variety of measuring techniques for determining reservoir surface areas extracted from Landsat MSS near-IR imageries of different scales and compared their accuracy with field data[4]. GIS is used for importing, analysing, modelling, visualizing, and reporting information for the reservoir and gives functionalities of spatial data management, mapping and analysis to assist decision-making[5][6]. The purpose of this study was to use satellite data and GIS to understand the sediment movement and accumulation in the reservoir.

2. Research Area and Satellite Data

Reservoir is used for vast area of society and different aspects because of valuable hydraulic structure for storage of water resource. The capacity of reservoir is continuously changing due to entering of eroded soils carried by water, wind, ice and movement of particles. A quantity of sediment is deposited annually and the loss of storage capacity due to reservoir sedimentation affects both obtains ability of water and operation schedules. Youngsan river in Gwangju carries about 0.3 million tons of sediments per year and Pyongdong reservoir located in Youngsan river falls in first quadrant of the scene covered by IRS path 36 and row 21. The water level in Pyongdong reservoir is normally full in the month of August and low in January[7]. Satellite images of those months were used for anlysis of sedimnetaion. The satellite data provided water spread area only, therefore additional field data like water level in the reservoir or elevation and original elevation-area-capacity curve were required. The data were collected from the office of the Water Management Engineer and Water Resources Department. The original elevation-area-capacity table was used to compare the present capacity and original capacity at selected elevations. The difference in the capacity was assumed as sediment deposit in the reservoir.

3. Materials and Method

ArcGIS and Earth Resources Data Analysis System(ERDAS) programs were used for spatial analysis of data and satellite images for deriving the land use and cover characteristics of the catchments. The analysis comprised of (1)digitization of base map of the reservoir, (2)geo-referencing of data, (3)water spread area estimation and estimation of revised reservoir capacity, and (4)loss in reservoir capacity due to sedimentation. Pyongdong reservoir and its catchment area was selected for the study and water spread boundary, drainage facilities, and road network were digitized and stored as vector layers. Figure 1 shows the study area which is Pyongdong reservoir located in Gwangju City. This base map was used for geo-referencing of all the satellite data.

Figure 1. Base map of Pyongdong reservoir.

The spatial disaggregation of the area into uniform cells was done to get these dimentation by using USLE along with determination of sediment delivery ratio and various parameters[8]. Using this method, we analysed and determined soil erosion and sediment yield in a reservoir watershed using GIS technique. Various favorable sedimentation thematic maps have been integrated into a single groundwater prospect zone with the application of GIS techniques. This required six steps, which are as follow:

- Geo-Referencing of satellie image
- Spatial database building
- Spatial database analysis
- Data integration through GIS
- Generation of groundwater potential zones map
- Calculation of the capacity of a reservoir

The satellite data used for this research had some geometric distortion and did not match exactly with each other. Therefore, geo-referencing was essential to make all images geometrically correct to overlay one over another for delineating contours of water spread at different levels. Satellite images include pixels or the components of image that represent the reflectance valuesof light spectrum[9]. ArcGIS was used for geo-referencing of satellite imageries of different dates and calculated the reflectance values in each band in satellite images and number of repetitions[10]. The mean values of the reflectance for each band were calculated in the basin of the watershed. The calculation of sediment based on the samples were carried at the hydrometric stations. Due to the lack of accurate statistics of the erosion and deposition of sediment at the watershed, the sediment measurement curve prepared by discharge and sediment concentration data or sediment discharge were used. At the hydrometric stations, sampling of suspended sediment concentration was carried out at the base discharges or in low flood discharges. However, the variability of flow and sediment relationships in flood discharges was much higher due to changes in rainfall and catchment(soil moisture, presence of sediment and subcortical water content) and thus, the efficiency of rating curve depended on the accuracy of the obtained data[11]. Considering the different reservoir levels between dead storage level and full storage level on various dates, original elevation-area capacity curve table and the reservoir level of year 2021 to 2022 were used in the analysis. For the determination of water spread area, it was required to find the number of continuous water pixels of the reservoir in the satellite imagery. Multiplying the number of water pixels with the area of individual pixel gave the water spread area of a reservoir. In the visible region of the spectrum(0.4-0.7μm), the transmittance of water is significant and the absorption and reflectance is low. In the region near the periphery of the reservoir, the water depth reduced gradually and the soil was saturated. The reflectance from this wetland along the periphery of the water spread area looked quite similar to the reflectance from the adjacent shallow water. To differentiate water pixels from the adjacent wetland pixels, comparative analysis of the digital numbers in different bands was carried out. The behaviour of the reflectance curves of water and soil-vegetation was different from the Band 2(0.53-0.59μm) onwards. Beyond Band 2, with increase in wavelength, water reflectance curves revealed downward trend while soil-vegetation curves showed upward trend. This characteristic could be used to differentiate the water pixels from the peripheral wetland pixels. A digital interpretation technique of the satellite data was followed to identify the water pixels. A ratio image was generated and values of water pixels were checked. In all the images, it was found that the ratio for water lies between 0.41-0.43. The volume of water that can be stored by the reservoir at a certain water surface elevation can be computed after determining the increment of storage between two elevations. After finalizing the water body areas for all the images, the histograms are analysed and the water pixels in each image are recorded. The water body area at any water level or elevation was obtained by multiplying the number of water pixels by the size of one pixel. The reservoir water level at the time of the satellite overpass was obtained from the reservoir authorities. The reservoir capacity between two consecutive reservoir elevations(ΔV) was computed using the prismoidal formula[12]:

$$\Delta V = \Delta H \, (A1 + A2 + \sqrt{A1 * A2}) / 3 \quad (1)$$

where ΔV is the volume between two consecutive elevations 1 and 2; A1 is the contour area at elevation 1; A2 is the contour area at elevation 2 and ΔH is the difference between elevation 1 and 2. The revised volume was compared with the original volume in each zone (obtained from the original elevation–capacity table) and the difference between the two represents the capacity loss due to sedimentation.

4. Results and Discussion

The IRS satellite data of 2021 and 2022 were obtained and image processing was carried out using Erdas Imagine. The revised volume of the reservoir was calculated using water spread area obtained from satellite data and respective elevations using cone formula. The revised cumulative capacities at various elevations were obtained by adding the revised volume between consecutive elevations and similar research was conducted by Cho[13]. The computation of revised capacity and the original capacity at different year is shown in the following Table 1.

Table 1. Computation of revised elevation area capacity table.

Years	Cumulative Capacity(Mft^3)	Original Volume(Mft^3)	% of Loss in Volume(Mft^3)
2021	84.2	22.8	13.2
2022	64.3	53.6	2.4

The difference between the original and revised cumulative capacity represented the loss in capacity due to sedimentation and dry season in winter. Cumulative capacities at different levels were also calculated and the revised live storage was estimated to 84.2Mft3 in 2021 and 64.3Mft3 in 20222 while the original capacity was 22.8 and 53.6Mft3 in 2021 and 2022. Therefore, the total loss in live storage capacity of Pyongdong reservoir comes out to be 15.6Mft3 over 2 year span. The hydrologic graph revealed the elevation vs. original and revised cumulative capacity of the reservoir. In addition to loss in live storage, there was loss in dead storage also. If we consider 20% loss in live storage, this would be 315.6*0.2=3.12Mft3.

5. Conclusion

In this study, the revised capacities of the Pyongdong reservoir was estimated with remote sensing and GIS technique. ArcGIS was used for geo-referencing of satellite imageries of different dates and calculated the reflectance values in each band in satellite images and number of repetitions. Integrated Land and Water Information System and ERDAS programs were used for spatial analysis of data and satellite images for deriving the land use and cover characteristics of the catchments. IRS-1C/1D, LISS-3 data of nine different dates for the year of 2021 and 2022 have been used for determination of revised water spread area. Using revised water spread obtained from the satellite data, the revised volume in between the successive intervals and revised cumulative capacities of the reservoir were analyzed and computed. With this research, we were able to give relative estimates of the erosion and sedimentation measures of Pynogdong reservoir. The following conclusions were drawn from the analysis of the results. From the analysis of remotely sensed data, it was found that the live storage of Pyongdong reservoir has reduced by 3.12Mft3. More loss in the live storage might be due to the accumulation of sediments in the lower zone. Satellite images for estimating sedimentation accumulation and loss has provided easy way to analyze since little fieldwork was required. The accuracy in determination of sedimentation rate was also better with the use of high resolution satellite data coupled with advance digital image processing technique. It would be appropriated if hydrographic surveys were conducted at longer interval and the remote sensing based sedimentation surveys were carried out at shorter intervals to make both surveys complementary to each other. These results indicate that applying GIS and image processing techniques could be effective in reducing sediment transport for ustainable water resources management in the basin. However, any implementation of catchment management measures to reduce sediment yields involves the use of resources and willingness of decision makers. This study shows that modelling approach could be helpful for decision makers to evaluate the cost and benefits of particular best management practices. For further model parameterization at a local scale should be done as more data and information become available.

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